Overview

Executive Summary

Acceleration limits are set in the x, y, and z axes for all mission phases to protect the crew from injury and other acceleration-related conditions. These limits are divided into two time regimes:

- sustained (> 0.5 seconds) and
- transient (≤ 0.5 seconds).

The standards are further divided according to whether the acceleration is:

- translational or rotational;
- the phase of flight;
- and whether the crew is standing or sitting.

Several countermeasures can be used to mitigate the effects of high acceleration loads. Additional factors such as parachute sway and seat angle need to be considered when assessing risk and developing solutions.

Requirements Overview:

V2 6064: *Sustained Translational Acceleration Limits*

V2 6065: *Rotational Velocity*

V2 6066: *Sustained Rotational Acceleration Due to Cross-Coupled Rotation*

V2 6067: *Transient Rotational Acceleration*

V2 6068: *Acceleration Rate of Change*

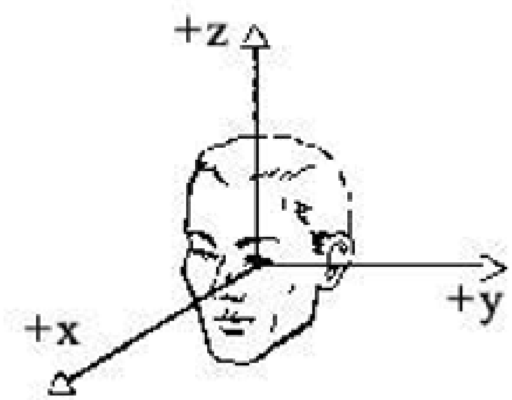
V2 6069: *Acceleration Injury Prevention*

V2 6070: *Injury Risk Criterion*

Background & Reference Data

Basis of current limits:

- Sustained: prior crewed vehicle data; human tolerance limits
- Transient: Apollo lunar landing impact data; Shuttle & ISS post-flight crew jump data; ISS inflight treadmill foot strike data



The Brinkley Dynamic Response Model

- Dynamic Response (DR)
    - Estimates the **transient** acceleration of the human body
    - A single degree of freedom lumped mass model
    - Calculated independently in each direction
    - Responses are highly specific for seat used in development
        - Changes to the seat, restraints and helmet can invalidate the model natural frequency and damping coefficient
        - Ground rules established to ensure model is valid to use
- Injury Risk Criterion (β)
    - Preset DR limits in each direction to estimate the injury risk
    - Estimates an injury risk but not severity or anatomical location
- Limitations
    - Subject pool limited to mostly young, male military volunteers
    - DR Limits based on limited statistical analysis of injury data
    - Limited validity in +X, -Z and ±Y axes

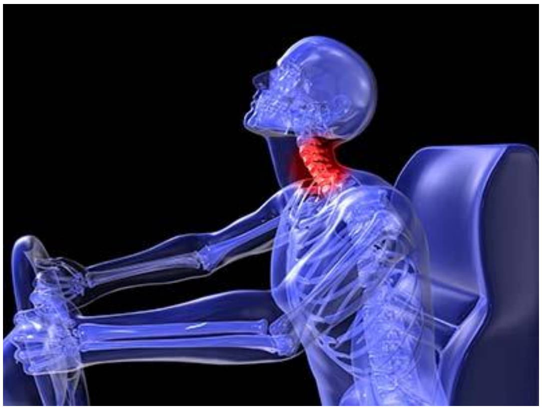
For information on how to use this model, see NASA/TM-2013-217380, Revision 1, Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Dynamic Events.

Health and Performance Risks of Excessive Acceleration Exposure

Sustained

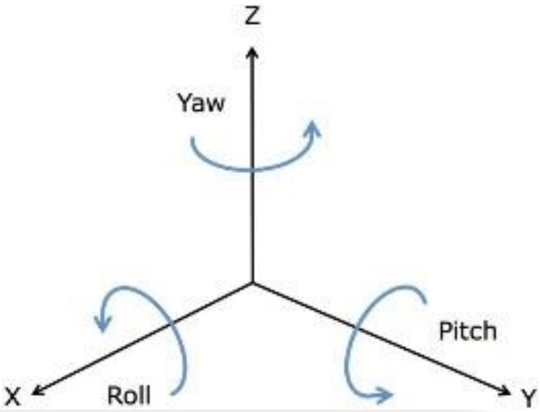
- Limited/difficulty of movement & breathing; unconsciousness
- See Standard V2 6064 in NASA-STD-3001, Volume 2 Figure 3 and 6 for limits and V2 6068 for rate of change

Transient



- Mostly traumatic injuries
- Vertebral injuries most common
- See Standard V2 6069 in NASA-STD-3001, Volume 2, Table 4 for limits

Rotational



- Disorientation; sickness; unconsciousness
- See Standard V2 6066-7 in NASA-STD-3001, Volume 2, for limits

Application Notes

Design Guidance

- Assumptions of the standing limits given in the requirements:
  - Additional equipment (suit) mass borne by the crewmember is <20% of the crewmember's shirtsleeve mass
  - Adequate restraint(s) are provided for all body postures

- Cross-discipline considerations
  - Critical to consider suit design and mass
  - Hard points on suit can cause injury during transient loads (landing)
  - Space between a crewmember and their suit, as well as the suit and the vehicle habitat, may cause physical harm

- Vibration & acceleration during dynamic phases of flight
  - If a crewmember is already experiencing high G loads (and subsequently limited movement), the effects of vibration on performance may be increased

- Potential countermeasures to orthostatic intolerance while standing
  - Physical/Vehicle (e.g. suit weight or bodyweight offloading, restraint systems)
  - Suit (e.g. anti-g suit, lower body compression)
  - Physiological (e.g. scheduled muscle contractions; breathing exercises; fluid loading and salt tablets)
  - All countermeasures should work concurrently to reduce risk and harm to the crew

- Considerations to meet transient and sustained loads requirements
  - Restraint systems during transition from microgravity
  - Offloading of suit mass that still enables crew performance
  - The suit, vehicle, seat and restraint systems must all interact conjointly to protect the crew from all types of acceleration loads
  - Seat design along with load attenuation is a critical design element that is critical in mitigating loads imparted to the crew member

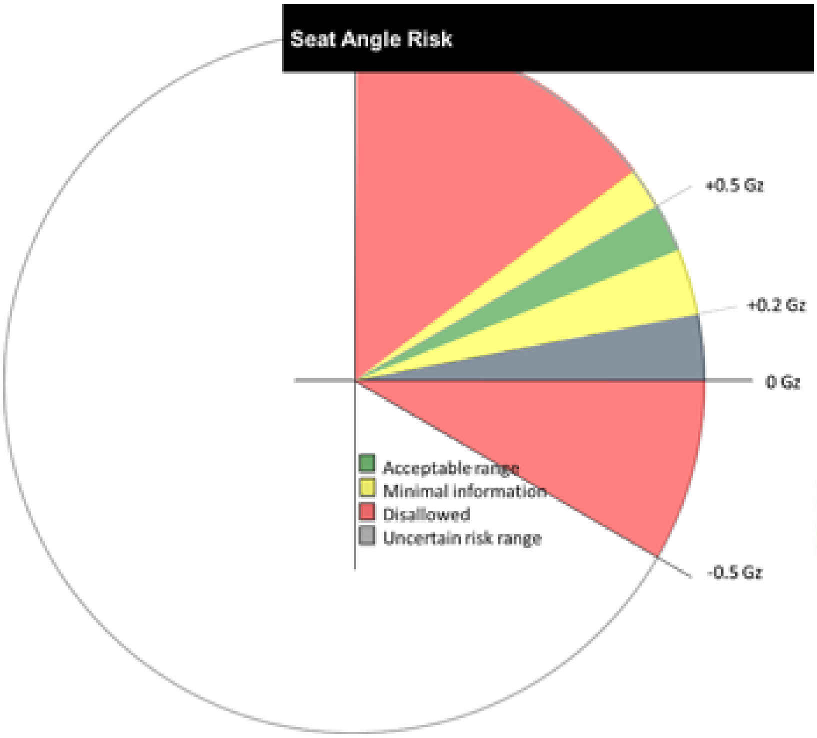
Application Notes

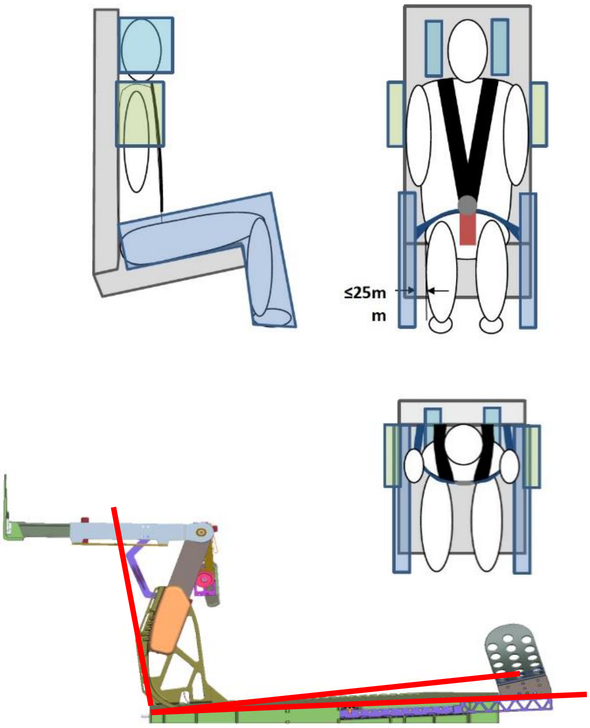
Design Guidance

Seat Angle

For impact tolerance, the +Gx orientation is the most advantageous direction of loading. In this orientation, humans can withstand much higher accelerations (by a factor of >2) than in other vectors. However, unless a vehicle lands with a zero downrange velocity, the landing impact will not be purely confined to a single axis. The +Gz orientation is most advantageous as the secondary impact vector due to increased tolerance and greater model fidelity in predicting injury.

In a vehicle with no roll control, any direction of impact is equally likely. In each vehicle case, an extensive assessment of nominal, off-nominal and contingency conditions would be necessary to accurately assess the risk to the crew due to impact. Depending on the direction of impact, different seat angles could either increase or decrease the risk of injury. A combination of roll control and a seat configuration that ensures a +Gx and +Gz impact is preferred.





Application Notes

Parachute Sway

As a capsule returns to earth with parachutes deployed, it is prone to swaying back and forth in the wind. Not only does this affect the angle of impact (by up to 24.5^{o}), but velocity of impact. The capsule will fall slower or faster depending on the angular position of the sway.

Figure 1. Pendulum motion under two Mains observed from chase helicopter during CDT-3-12.

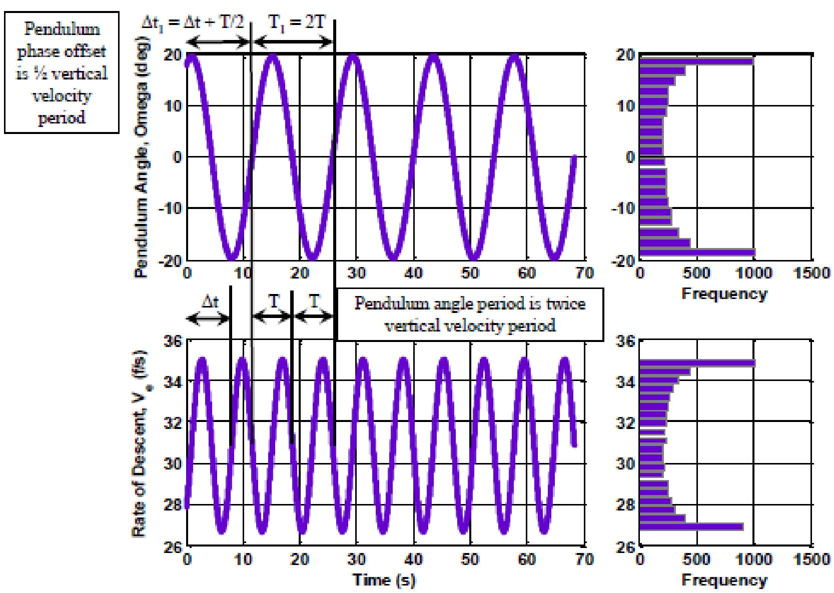


Figure 4. Relationship between pendulum swing angle and vertical velocity component.

Shortening parachute riser length to reduce the distance between the parachute and payload has been shown to mitigate sway during descent. Additionally, an Over-Inflation Control Line reduces swing amplification by restricting the canopy diameter.

Reference: AIAA 2015-2138, Pendulum Motion in Main Parachute Clusters, Ray et al, April 2015